

Deep Space Network, Cryogenic HEMT LNAs



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Communications Ground Systems Section

August 17, 2006

Symposium Internacional de Telematica Deep Space Network, Cryogenic HEMT LNAs

Abstract



Exploration of the Solar System with automated spacecraft that are more than ten astronomical units (1 AU = 149,597,870.691 km) from earth requires very large antennae employing extremely sensitive receivers. A key figure of merit in the specification of the spacecraft-to-earth telecommunications link is the ratio of the antenna gain to operational noise temperature (G/T_{op}) of the system. The Deep Space Network (DSN) receivers are cryogenic, low-noise amplifiers (LNAs) which address the need to maintain T_{op} as low as technology permits.

Historically, the extra-ordinarily sensitive receive systems operated by the DSN have required cryogenically cooled, ruby masers, operating at a physical temperature near the boiling point of helium, as the LNA. Although masers continue to be used today, they are hand crafted at JPL and expensive to manufacture and maintain. Recent advances in the development of indium phosphide (InP) based high electron mobility transistors (HEMTs) combined with cryogenic cooling near the boiling point of hydrogen have made this alternate technology comparable with and a fraction of the cost of maser technology. InP HEMT LNA modules are demonstrating noise temperatures less than ten times the quantum noise limit ($10hf/k$) from 1 to 100 GHz. To date, the lowest noise LNA modules developed for the DSN have demonstrated noise temperatures of 3.5 K and 8.5 K at 8.5 K at 32 GHz, respectively. Front-end receiver packages employing these modules have demonstrated operating system noise temperatures of 17 K at 8.4 GHz (on a 70m antenna at zenith) and 39 K at 32 GHz (on a 34m antenna at zenith).

The development and demonstration of cryogenic, InP HEMT based front-end amplifiers for the DSN requires accurate component and module characterization, and modeling from 1 to 100 GHz at physical temperatures down to 12 K. The characterization and modeling begins with the HEMT chip, proceeds to the multi-stage HEMT LNA module, and culminates with the complete front-end cryogenic receiver package for the antenna.

This presentation will provide an overview of this development process. Examples will be shown for devices, LNA modules, front-end receiver packages, antennae employing these packages and the improvements to the down-link capacity.

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Abstract



La exploración del sistema solar por medio de naves espaciales automatizadas que se encuentran a mas de diez unidades astronómicas de la tierra (la distancia media de la nave espacial y la tierra se utiliza como la Unidad Astronómica), requieren antenas de gran superficie, en conjunto se integran a receptores de alta sensibilidad. Un mérito fundamental en la unión de las telecomunicaciones entre la nave espacial y la tierra es la proporción de la ganancia de la antena y la temperatura del ruido operativo/funcional del sistema, G/T. Los receptores de DSN (Deep Space Network, red para el espacio lejano) son amplificadores criogenitos "cryogenic" (que funcionan a temperaturas sumamente bajas) y tienen un nivel de ruido muy bajo (LNAs), lo cual indica la necesidad de mantener la temperatura de ruido operativo tan bajo como la tecnología lo permita.

Históricamente, los sumamente sensibles sistemas de recepción que usa el DSN han necesitado de un cristal sintético de rubí, situado en un fuerte campo magnético y superenfriado con helio líquido hasta cerca del cero absoluto como un LNA "ruby-masers" (maser - palabra formada por las siglas de la descripción en inglés del proceso amplificador "Microwave Amplifier by Stimulated Emission of Radiation", cuya traducción es "Amplificación de microondas por la emisión estimulada de radiación"). Aun cuando los "masers" continúan siendo usados hoy en dia, estos son hechos a mano en Jet Propulsion Laboratory (JPL), la fabricación y mantenimiento de los mismos son sumamente costosos. Avances recientes en el desarrollo de los transistores de electrones de alta movilidad con base en "indium phosphide (InP) (HEMTs) en conjunto con enfriamiento "cryogenic" cerca del punto de bullición del hidrógeno, han logrado que esta tecnología alternativa sea comparable a la tecnología del maser a una fracción del costo. Módulos InP HEMT LNA han demostrado un nivel de ruido muy bajo, menos de diez veces que la del límite del ruido "quantum" ($10hf/k$) de 1 a 100 GHz. Hasta el momento, los módulos LNA de mas bajo ruido electrónico desarrollados por el DSN han demostrado "ruido de temperaturas" de 3.5K y 8.5K a 8.5 GHz y 32 GHz respectivamente. "Front-end receiver packages" que emplean estos módulos han demostrado temperatura de ruido operativo/funcional de 17 K a 8.4 GHz (en una antena de 70m al zenith).

El desarrollo y demostración del amplificador InP HEMT "based front-end" "cryogenic" a temperaturas extremadamente bajas para el DSN requiere una caracterización del componente del módulo con exactitud y el modelaje "modeling" desde 1 a 100GHz a temperaturas físicas de hasta menos de 12 K. La caracterización y modelaje empieza con el HEMT "chip" y procede con el módulo HMT LNA multifacético "multi-stage" y culmina con "complete front end cryogenic receiver package" para la antena.

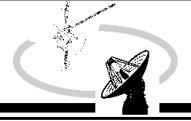
Esta presentación proveera una visión general de este proceso de desarrollo con énfasis en la comparación entre resultados modelados y resultados medidos a 8.4 GHz. Los resultados mostrados serán para aparatos, módulos LNA, "front end receiver packages" que usan estos módulos, las antenas que emplean estos "packages" y las mejoras hechas a "down link capacity".

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Outline



- 1. Introduction**
- 2. Deep Space Exploration**
- 3. Current Missions**
- 4. Telecommunication Challenges**
- 5. Deep Space Network**
- 6. Front-end Cryogenic LNA Development**
- 7. Conclusion**

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Jet Propulsion Laboratory

- Has a dual character:
 - Unit of Caltech, staffed with Caltech employees; founded in 1936 by graduate student, F. Malina, and Professor von Kármán
 - Federally Funded Research and Development Center (FFRDC) under NASA sponsorship; JPL led the development of US rocket technology in WWII.
- Is a major national research and development (R&D) center supporting:
 - NASA programs
 - Defense programs
 - Civil programs of national importance compatible with JPL capabilities.
- Enables our nation to explore space for the benefit of humanity:
 - Exploring our own and neighboring planetary systems
 - Making critical measurements to understand our home planet and help protect its environment
 - Applying JPL's unique skills to solve problems of national security and national significance
 - Inspiring the next generation of explorers.

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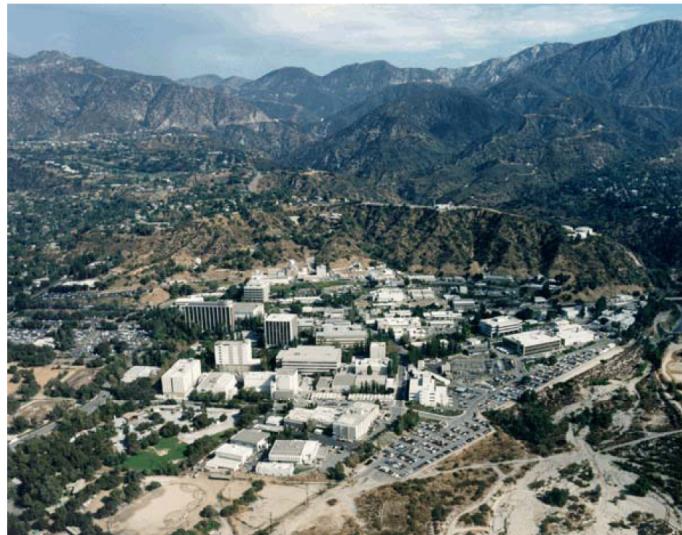


Photo of the JPL, nestled adjacent to the Arroyo Seco at the foot of the San Gabriel Mountains, Pasadena

- 5000 + employees
- 177 acres
- 134 buildings and 57 trailers

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Funding Sources



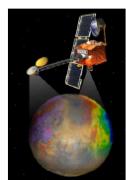
- **Internal – Directorates**
 - Planetary Flight Projects – 38%
 - Solar System Exploration Programs- 10%
 - Astronomy and Physics – 20%
 - Earth Science and Technology – 16%
 - Interplanetary Network – 13%
 - Other Offices – 3%
 - R&TD Strategic Initiatives and Spontaneous Concepts
 - Director's and President's Discretionary Funds
 - Student and Faculty Summer Positions
- **External**
 - DARPA
 - NSA
 - USAF

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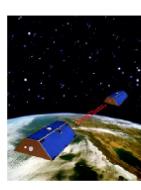
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Current Missions and Projects



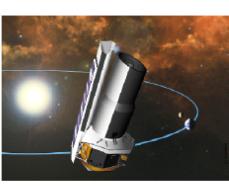
2001 Mars Odyssey began mapping February 2002



GRACE Earth gravity measuring mission launched March 17, 2002



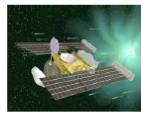
GALEX ultraviolet observatory launch in March 2003



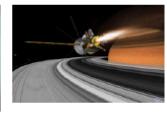
NASA infrared great observatory SIRTF launch in April 2003



Mars Exploration Rovers launch summer 2003, arrive January 2004



Stardust captures material from Comet Wild 2 in January 2004



Cassini/Huygens arrives at Saturn July 2004



Genesis solar wind sample return September 2004



Cloudsat launch November 12, 2004

A sample of current spacecraft, instruments and missions

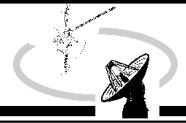
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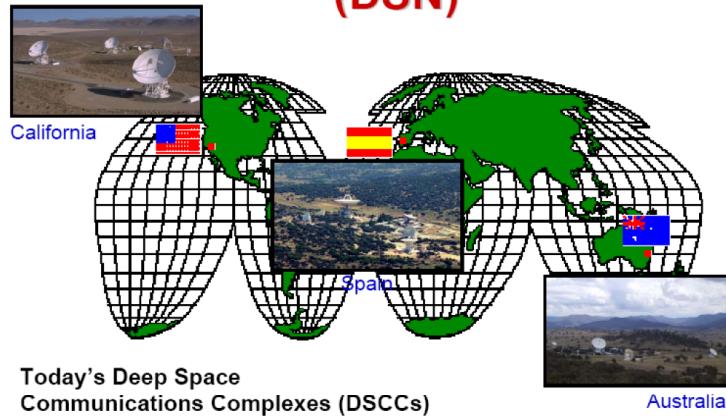
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DSN Complexes

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(DSN)



- The DSN operates a complex of 34m and 70m antennas world-wide at frequencies of 2.3, 8.4 and 32 GHz.

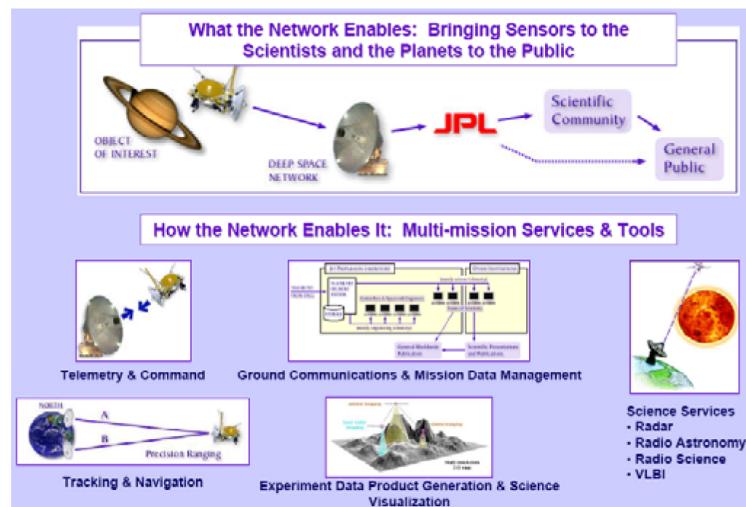
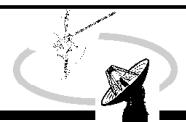
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DSN Resources

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The DSN serves scientists and the public.

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Resources: Ground System Overview**

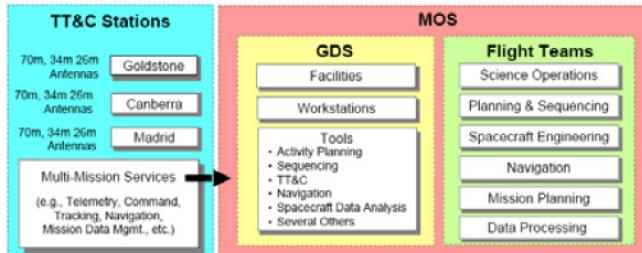
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JPL Deep Space Definition:

Ground System = TT&C Stations + MOS
MOS = GDS + Flight Teams

TT&C = Tracking, Telemetry, & Command
GDS = Ground Data System
MOS = Mission Operations System



Some key differences from other ground systems:

- Distributed operations (e.g., spacecraft ops, science ops, data acquisition, etc.)
- Each mission is unique, requiring unique tool adaptations
- Interoperability with international mission GDS's and tracking assets
- Signal-to-Noise-Ratio-constrained TT&C; long two-way light times
- Exotic tracking & navigation techniques; no GPS
- Integrated suite of multi-mission tools and services

Simplified Ground telecommunications systems overview

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Telecommunication Challenges**

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Fundamental Obstacles

- **Extreme distance** – communicating at Neptune (30 AU) is ~10 billion times more difficult than at a commercial GEO satellite distance.
- **Long Round Trip Light Times** – over 8 hours at Neptune; no “joy-sticking” possible.
- **Unique Navigation Scenarios** – small body ops, gravity assist trajectories, aerocapture/aerobraking, low-thrust propulsion, Lagrange point missions, formation flying.
- **High Launch/Delivery Cost per Unit Payload Mass** – drives need for low mass, low power flight systems.



Programmatic “Bottlenecks”

- **Deep Space Network Congestion** – compromises science return and adds risk to all missions (e.g., Mars '03-'04).
- **Limited Connectivity at Mars** – Mars science orbiters provide only limited relay communications for surface vehicles; little or no communications during many critical events.
- **Aging Assets & Insufficient Bandwidth** – ~30-year old 70m antennas; very low data rates from planets; can only map ~1% of Mars at high resolution due to data rate constraints.
- **Increasing Operations Complexity** – scientists spend more time on operations than science; more multi-element missions will increase this complexity.

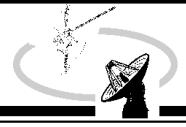
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Solutions and Approaches**

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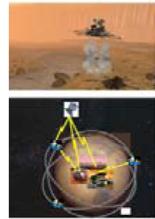
DSN/Flight Comm. Upgrades

- Ka-band
- Automation
- 1 new antenna
- Advanced spacecraft antennas, amplifiers, and radios



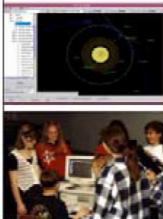
Next Generation DSN Prototypes

- Optical communications
- Arrays of small microwave antennas



Mars Comm Relays

- Automated relay and switching H/W, S/W
- Micro-terminals for landers
- Dedicated Mars relay orbiters



Applications

- Automated tools for operations
- Science data visualization and analysis tools
- "Killer applications" for public participation

Research and Development at a variety of technology readiness levels.

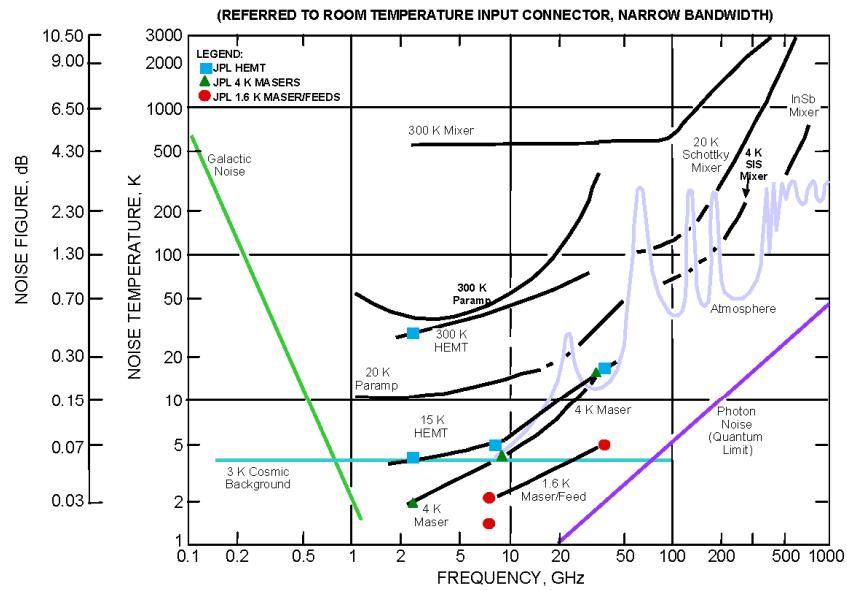
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Received Spacecraft Signal Challenges**

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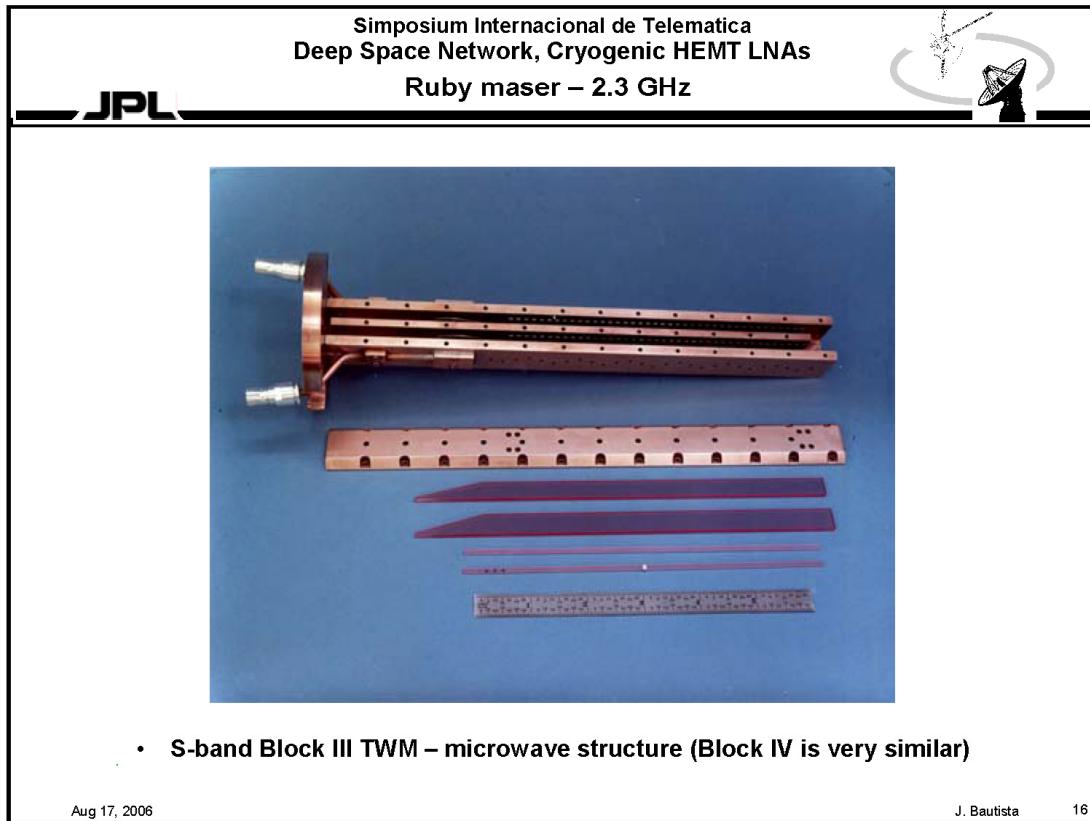
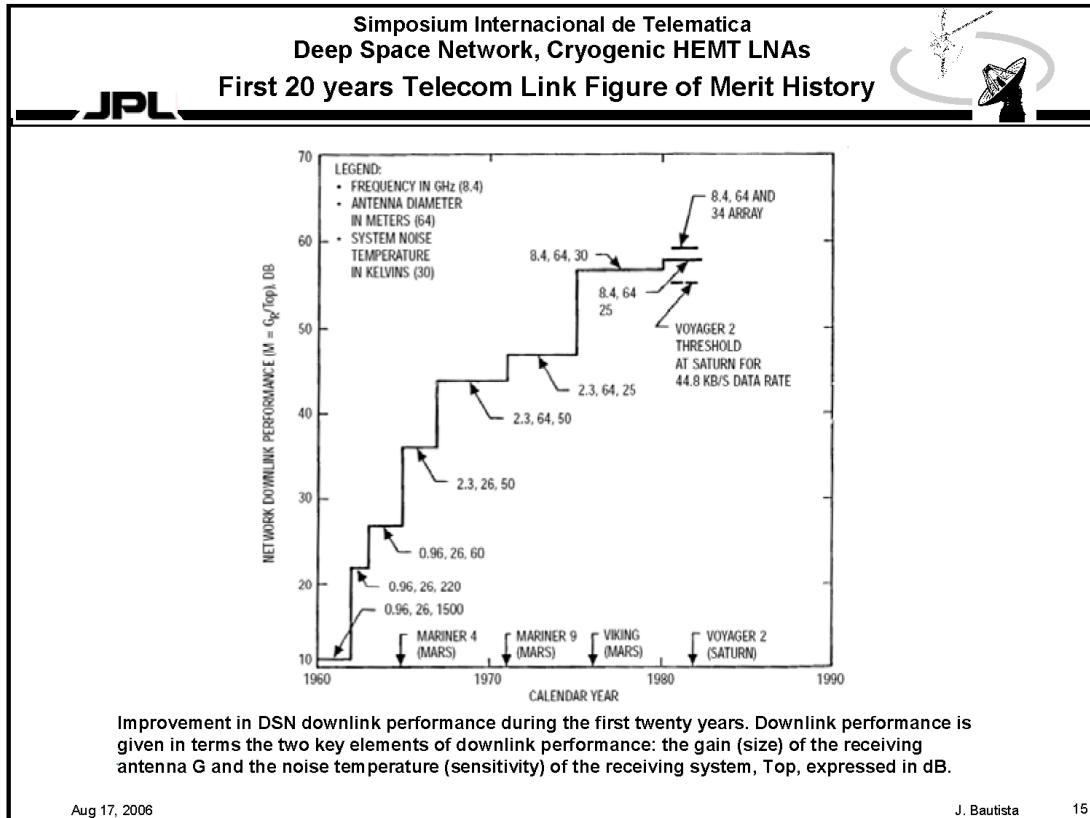


Low Noise Amplifier Performance and Background Noise

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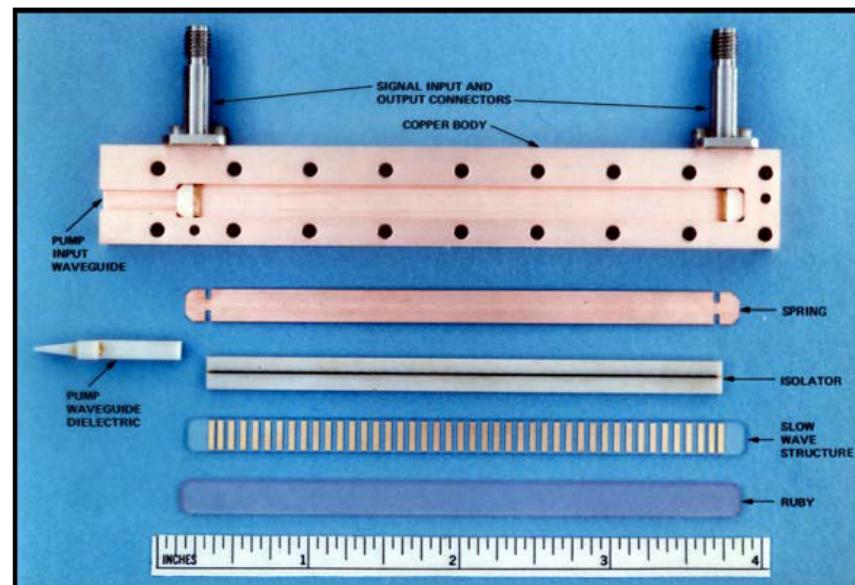
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8.45 GHz Ruby maser

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X-band traveling wave maser microwave structure

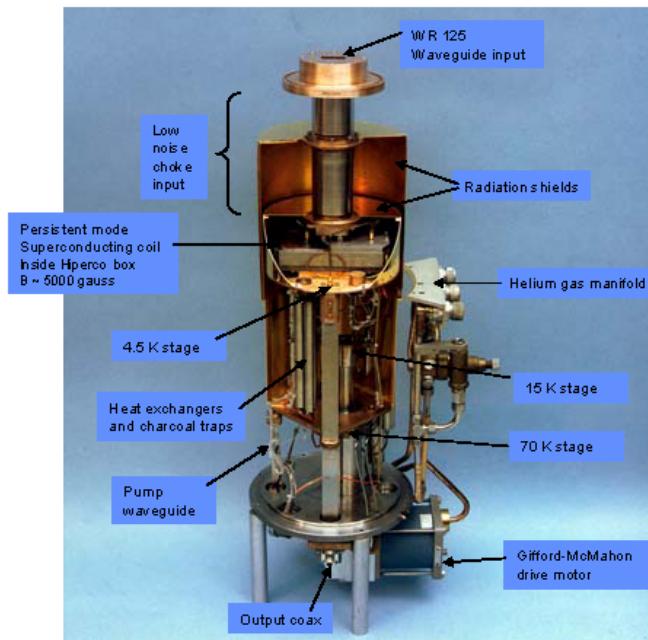
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Block IIA X-band maser in a 1 watt 4.5 K CCR

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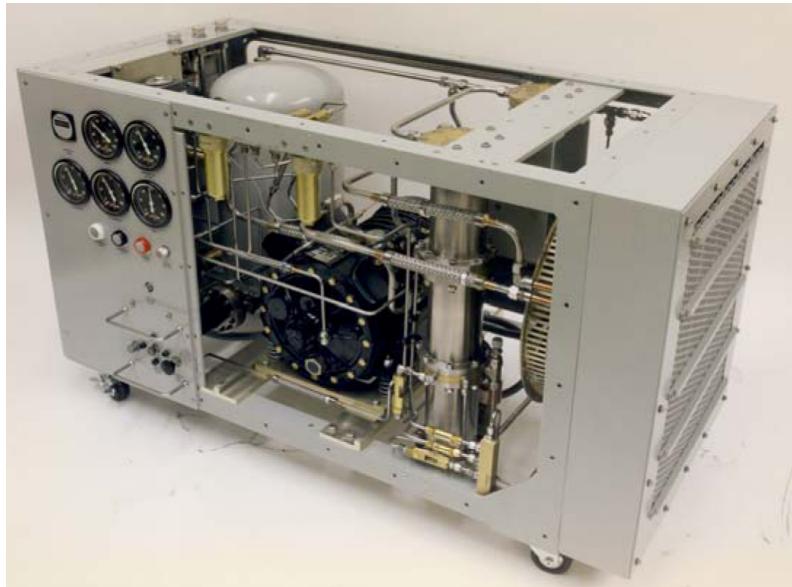
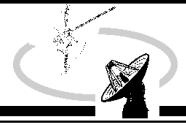
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Ruby maser Helium compressor

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5 HP Helium compressor for 15 K Gifford-McMahon and Joule Thomson loop

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Resources: HEMT Technologists

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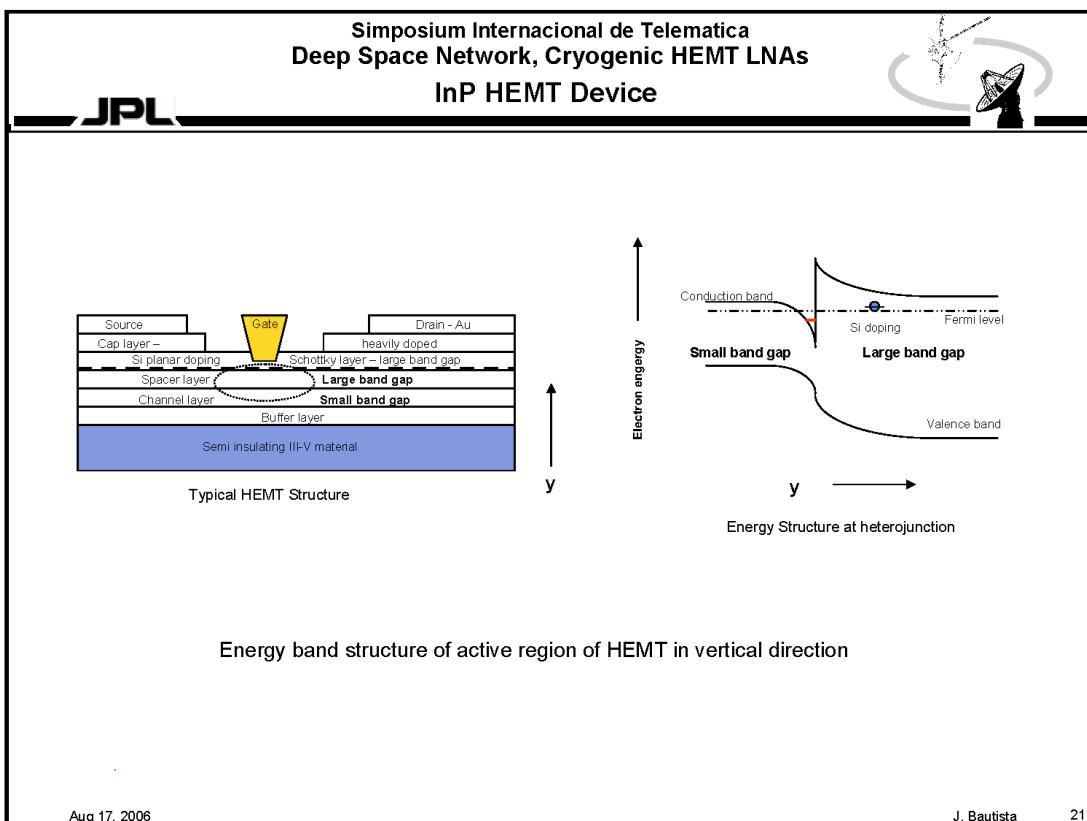
J.G.Bowen, J.F.Davis, J.E. Fernandez, B. Fujiwara, T. Gaier,
T. Hansen, E. Long, J. Loreman, M. Morgan, G.Ortiz, S.M.Petty,
R. Quinn, S.Montanez, D. Neff, M. Pospieszalski, J.L. Prater,
J.S. Shell, M. Tsai, N. Wade Falk, S. Weinreb
Jet Propulsion Laboratory
R. Grundbacher, R. Lai, M. Nishimoto
NGST (TRW), Inc.
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Georgia Institute of Technology
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InP HEMT Device**

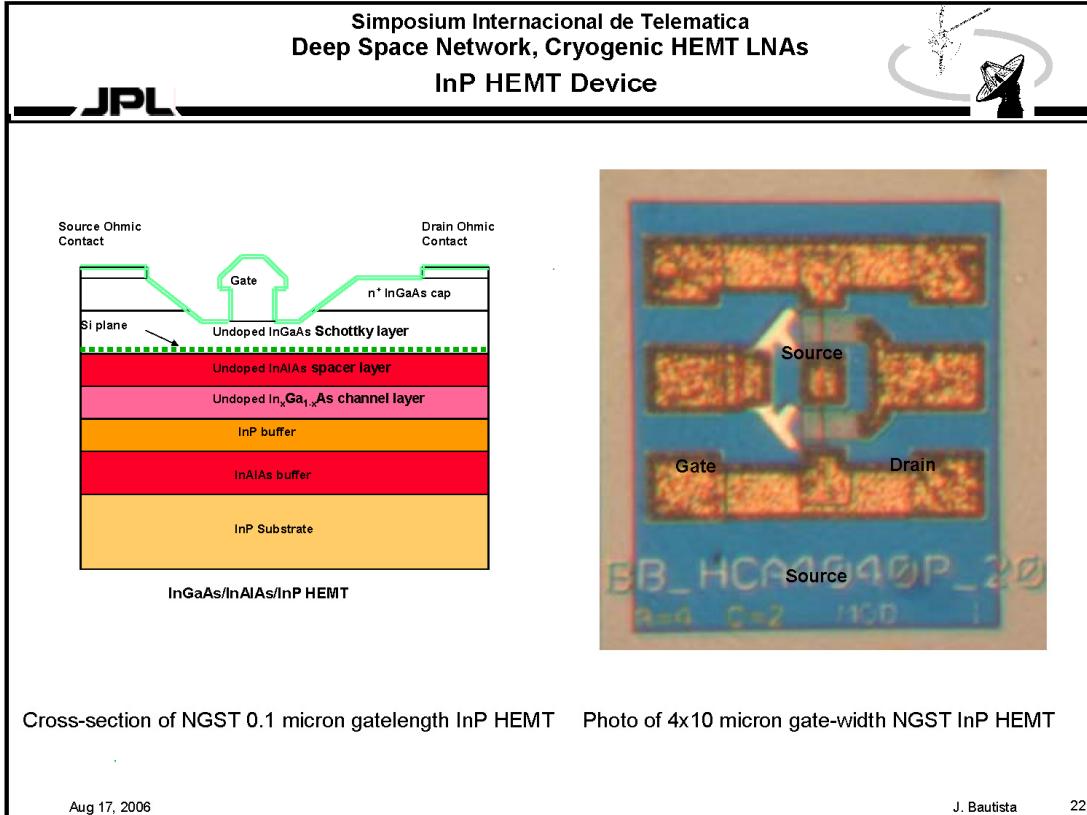


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InP HEMT Device**



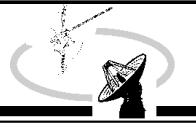
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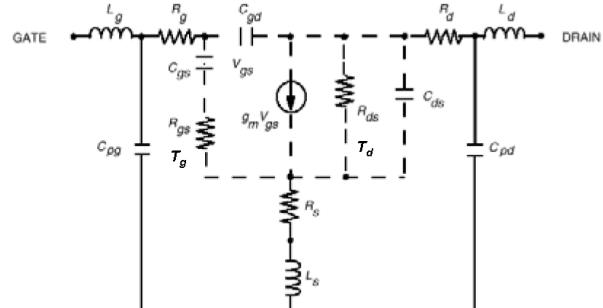
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Device Noise and Small Signal Model**

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Pospieszalski Small Signal HEMT Noise Model



Low Frequency Noise Parameters

$$T_{\min} = \frac{2\alpha C_{gs}}{g_m} \sqrt{g_{ds} T_d r_{gs} T_g} \quad R_{opt} = \frac{g_m}{\alpha C_{gs}} \sqrt{\frac{r_{gs} T_g}{g_{ds} T_d}} \quad X_{opt} = \frac{1}{\alpha C_{gs}} \quad g_n = \frac{T_{\min}}{2R_{opt} T_o}$$

$$\text{for } \frac{\omega}{\omega_i} \leq \sqrt{\frac{T_g}{r_{gs} g_{ds} T_d}} \quad \text{and} \quad r_{gs} \leq R_{opt}$$

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Solution: Cryogenic Cooling of LNA**

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Noise Temperature Budget

Frequency	8.4 GHz	32GHz
Antenna Site	DSS14	DSS13
Diameter	70-m Cassegrain	34-m BWG
Cosmic Background	2.5K	2.0K
Atmosphere (Clear)	2.1K	8.1K
Antenna	3.8K	12.9K
Feed Components	T _{feed}	T _{feed}
LNA Package	T _{LNA}	T _{LNA}
Follow-up Receiver	0.1K	0.4K
Top	T _{LNA} + T _{feed} + 8.5K	T _{LNA} + T _{feed} + 23.4K

LNA Noise Temperature Contribution

Component(s)	Noise Temperature Contribution	Physical Temp Dependence
HEMT Device	$T_{\min} = \frac{2\alpha C_{gs}}{g_m} \sqrt{g_{ds} T_d r_{gs} T_g}$	$T_g, g_m(T_g)$
LNA Module	$T_{LNA} = T_{\min 1} + \frac{T_{\min 2}}{G_1} + \frac{T_{\min 3}}{G_1 G_2}$	$T_{\min}(g_m), G_i(g_m)$
LNA CCR Package	$T_e = \frac{[(L-1) + \Gamma_L^2] T_L + L T_{LNA}}{(1 - \Gamma_L^2)}$	T_L

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NGST InP HEMT MMIC LNA Wafer**

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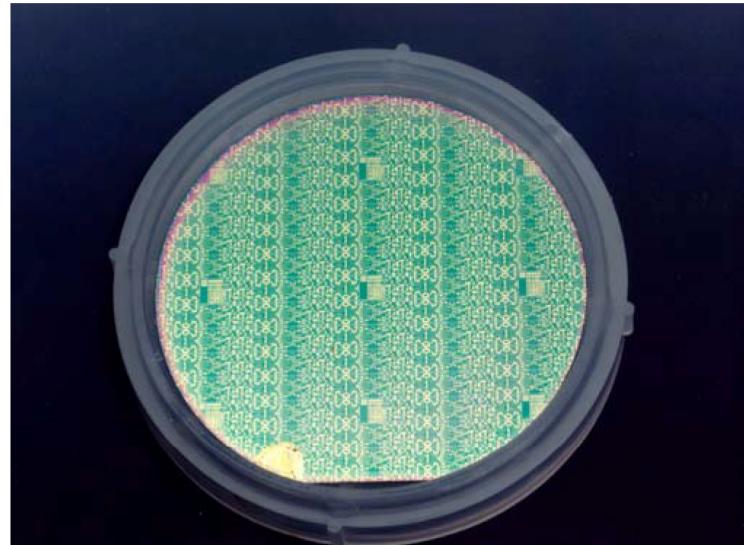
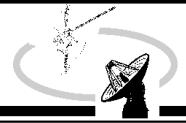


Photo of NGST InP MMIC LNA wager for the DSN Array

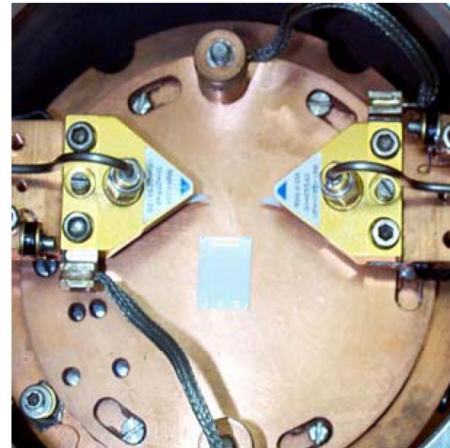
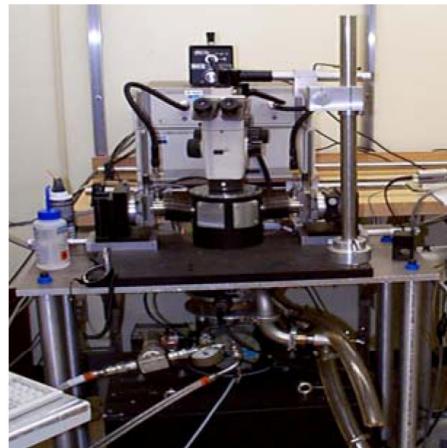
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Device Characterization and Modeling**

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Photograph of Cryogenic Probe Station

Photograph of Cryogenic Chamber Interior

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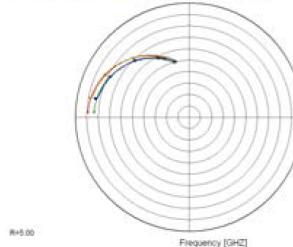
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Noise and Small Signal Modeling**

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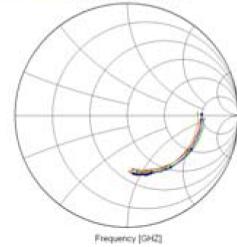
S-parameters, measured vs modeled at Cryo Temp with(+) and without(-) illumination for Cryo3-041 60 micron HEMT biased @ (Vd(-)=0.55v, Id=1.81mA; Vg=0.150, Ig=0.142 uA & Vd(+)=0.55v, Id=2.4mA; Vg=0.150, Ig=0.124 uA

TRW Cryo3 -4f60 umicron Cryo3-041
MMICAD - Tue Aug 21 18:57:07 2001



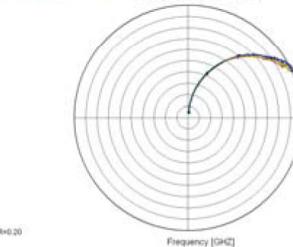
Frequency = 1 to 35 GHz

TRW Cryo3 -4f60 umicron Cryo3-041
MMICAD - Tue Aug 21 18:52:41 2001



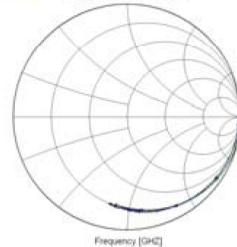
Frequency [GHz]

TRW Cryo3 -4f60 umicron Cryo3-041
MMICAD - Tue Aug 21 18:55:40 2001



Frequency [GHz]

TRW Cryo3 -4f60 umicron Cryo3-041
MMICAD - Tue Aug 21 18:54:28 2001



Frequency [GHz]

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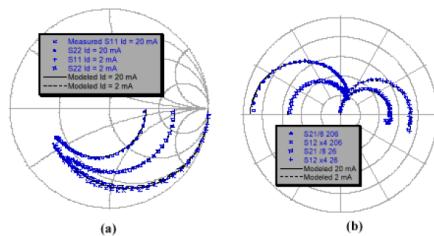
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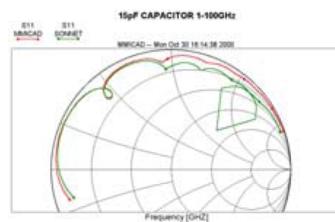
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Device & Passive Component Modeling & Characterization

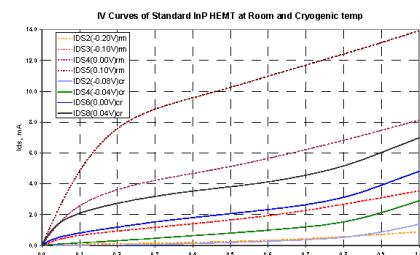
Measured and modeled S-parameters at 18 K of Ka-band TRW InP HEMT for two currents: 2 and 20 mA



2-D vs 2¹/₂-D bias capacitor model



IV Curves for Ka-band HEMT at 296 and 18K

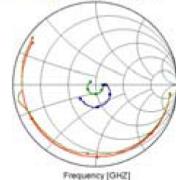


Measured and modeled S-parameters at 18 K of 1Kohm bias resistor from 2 to 40GHz

Bias Component Models

S11 BiasModel S21 BiasModel S11 BiasTROTE Model S21 BiasTROTE Model

MMICAD - Tue Oct 31 08:30:40 2000



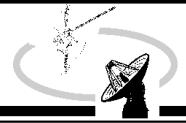
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LNA test fixture and module assembly**

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MIC and MMIC LNA module assembly facility

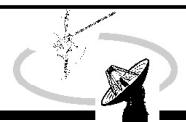
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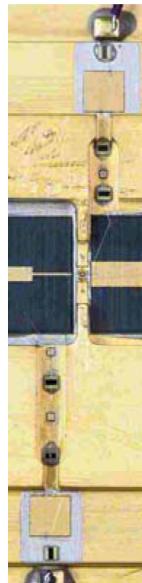
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LNA Modeling and Characterization**

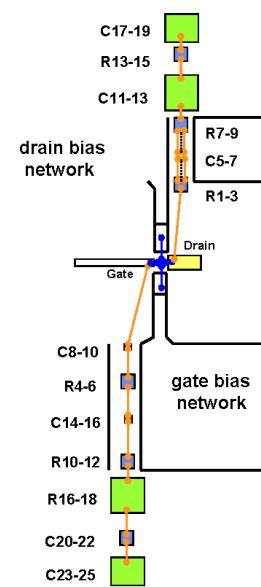
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X-band HEMT LNA 2nd Stage Photo



X-band HEMT LNA 2nd Stage Schematic

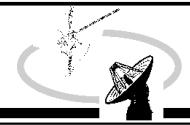


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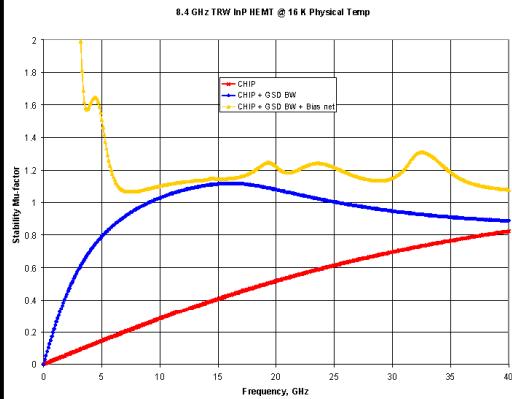
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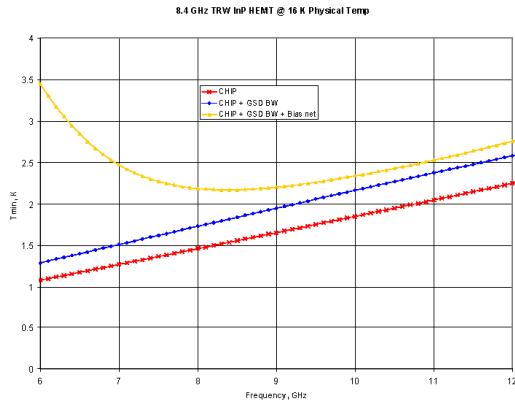
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 LNA Design Approach and Modeling at X-band**



Broadband single stage stability - model



In band single stage noise temperature - model



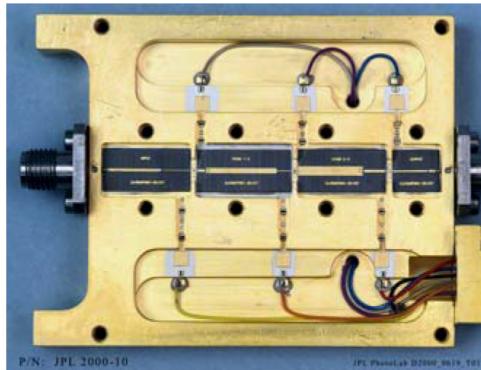
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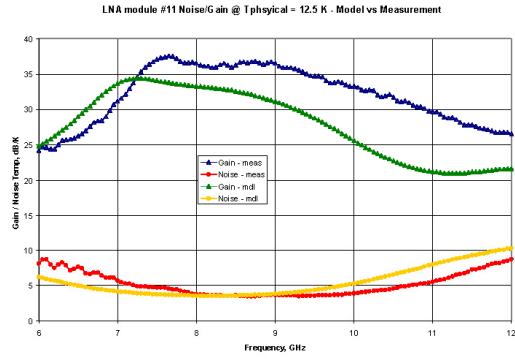
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 LNA Modeling and Characterization**



Photo of three-stage 8.4GHZ InP LNA module



Measured and modeled Noise/Gain of three-stage 8.4GHZ InP LNA module



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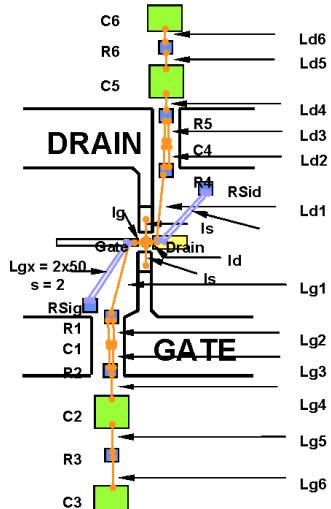
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 Deep Space Network, Cryogenic HEMT LNAs
 LNA Design Approach and Modeling at Ka-band**

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Ka-band LNA "unit amp" stability for 60- and 80- micron Cryo-041 InP HEMT Model



Schematic of "unit amp"



Stability, Mu-factor, of 60 and 80 micron "unit amps"

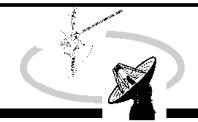
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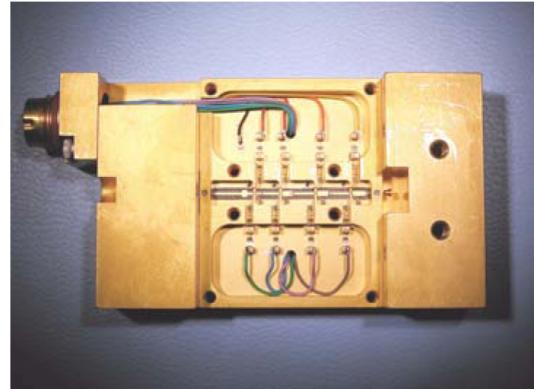
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 InP MIC and MMIC LNA Modules**

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Breadboard Array Ka-band, 3-stage MMIC LNA utilizing NGST InP HEMTs



DSN Ka-band 4-stage MIC LNA NGST InP HEMTs.

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LNA Modeling and Characterization

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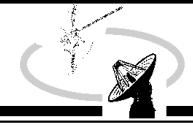
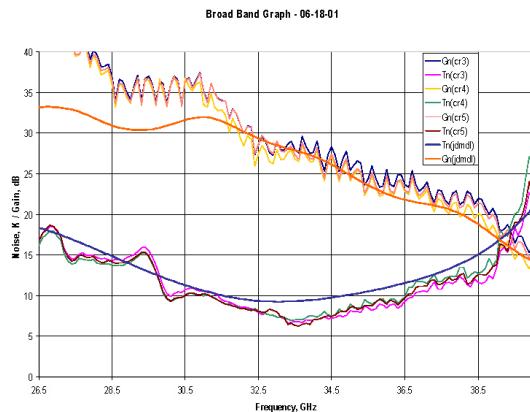


Photo of Cryogenic, Ka-Band LNA dual-module test bed



**Measured and modeled (including wave-guide flange at input and output)
Noise/Gain of four-stage 32GHZ InP LNA module**

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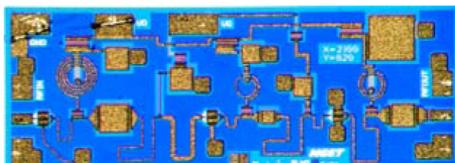
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DSN InP MMIC LNAs

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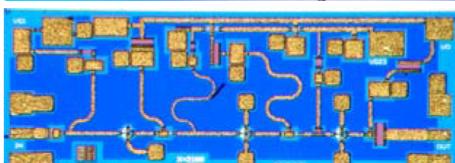


CRYO-10 MMIC LNA Device Designs



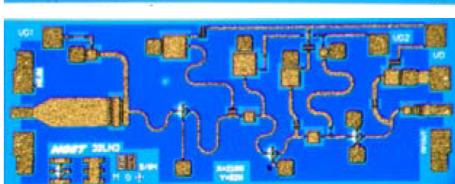
6LN2B

- Designed by Niklas Wadefalk
- 6-12 GHz Single Ended LNA
- 3 Stage - 4X50um InP HEMT Transistors



32LN1G

- Designed by Yulung Tang
- 26-40 GHz Single Ended LNA
- 3 Stage - 4X15um InP HEMT Transistors



32LN3

- Designed by Niklas Wadefalk
- 26-40 GHz Single Ended LNA
- 3 Stage - 4X10um InP HEMT Transistors

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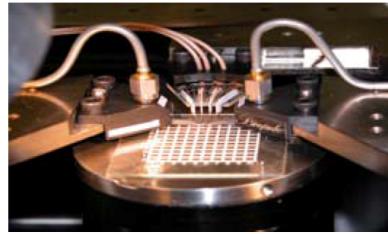
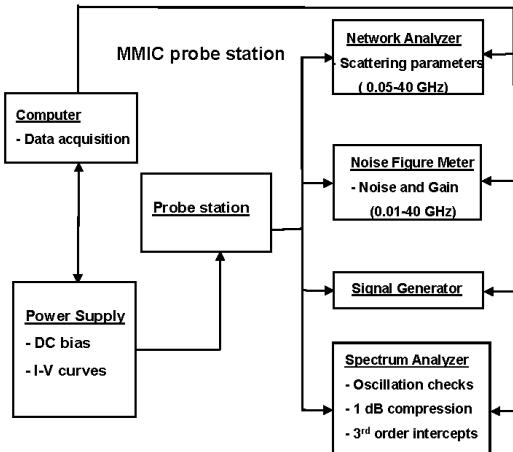
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InP MMIC LNA Modeling and Characterization



Room Temperature Wafer Probe Station

Used to select MMICs for use in the DSN array. The wafer probe testing allows the modules to be built using devices that are likely to have good performance. The selection of low noise devices is done largely on the basis of gate leakage current.



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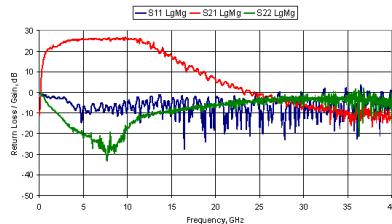
37

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InP MMIC LNA Modeling and Characterization

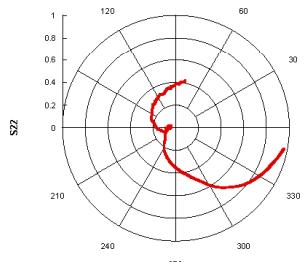


Typical X-band and Ka-band MMIC data obtained with the probe station. The data includes input and output reflection coefficients, forward transmission gain, and polar plots of output reflection coefficient.

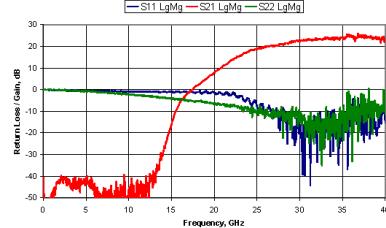
6LN2B Wafer: Cryo-10 Lot: 4292-014 R7 C1 M0



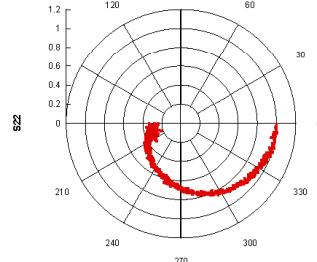
X-band data 6LN2B Wafer: Cryo-10 Lot: 4292-014 R7 C1 M0



32LN1G Wafer: Cryo-10 Lot: 4292-012 R6 C3 M1



Ka-band data 32LN1G Wafer: Cryo-10 Lot: 4292-012 R6 C3 M1



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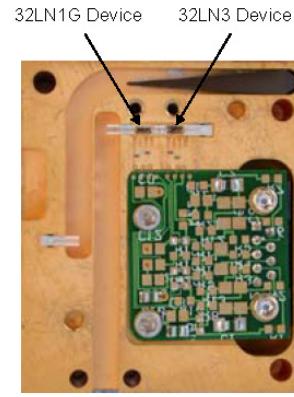
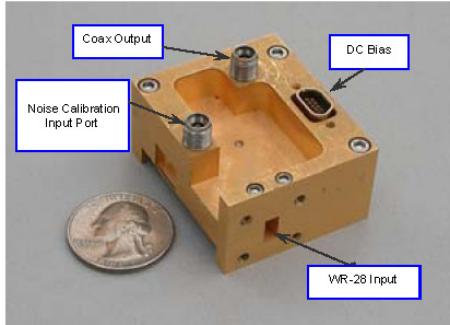
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 InP MMIC LNA Modeling and Characterization**



Ka-Band MMIC HEMT Module Utilizing 32LN1G and 32LN3 Devices

- Designed by Matthew Morgan
- 10 – 15 K Noise Temperature @ 12 K Tph
- 40 – 45 dB Gain
- 26.5 – 40 GHz



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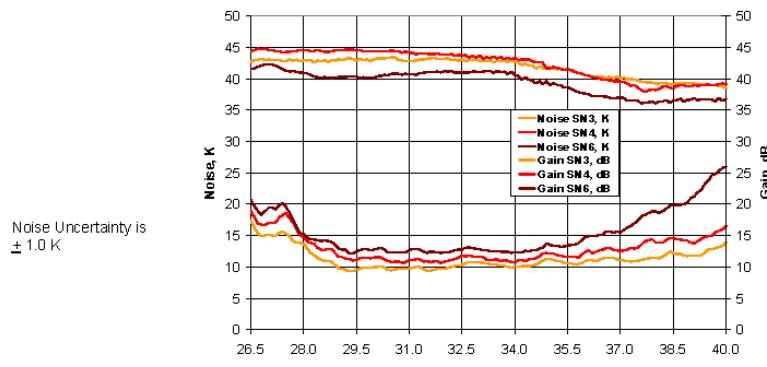
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 InP MMIC LNA Modeling and Characterization**



Ka-band MMIC Module Cryogenic Noise / Gain Data

MMIC: 32LN1G & 32LN3, Wafer: Cryo-10, Lot: 4292-014



DC Bias Values

LNA #	Vd1, v	Id1, mA	Vg1, v	Ig1, uA	Vd2, v	Id2, mA	Vg2, v	Ig2, uA
Sn03	0.65	9.5	0.15	0.60	0.8	9.4	0.15	1.0
Sn04	0.8	10	0.1	0.6	0.8	17	0.24	3.5
Sn06	0.7	10	0.1675	1.1	0.9	10	0.135	0.3

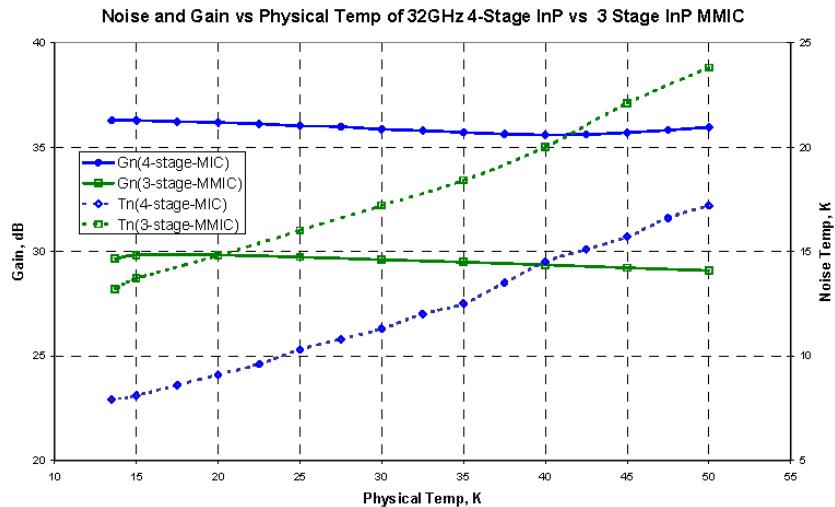
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 InP MIC vs MMIC LNA Performance**

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Noise temperature performance vs physical temperature at 32 GHz of a 4-stage MIC LNA and 3-stage MMIC LNA utilizing NGC InP HEMTs.

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 DSN Large Aperture and Large Array Cryogenic LNAs**

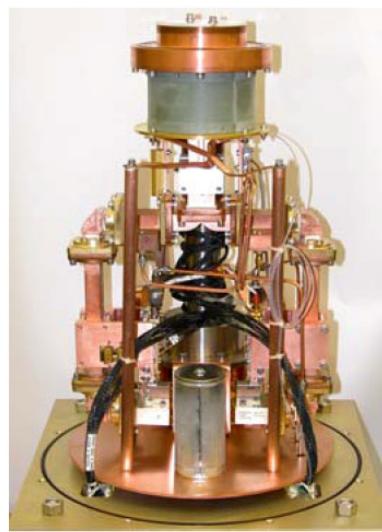


Photo of DSN Dual Channel InP HEMT/CCR



Photo of Array InP HEMT-MMIC/CCR

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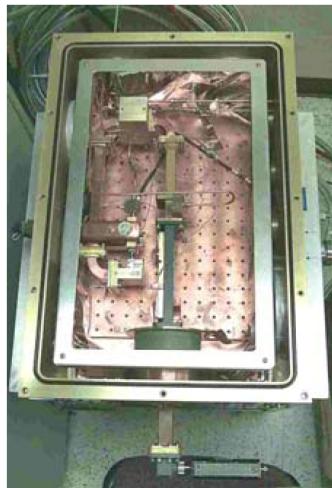
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Subsystem Measurements and Results**

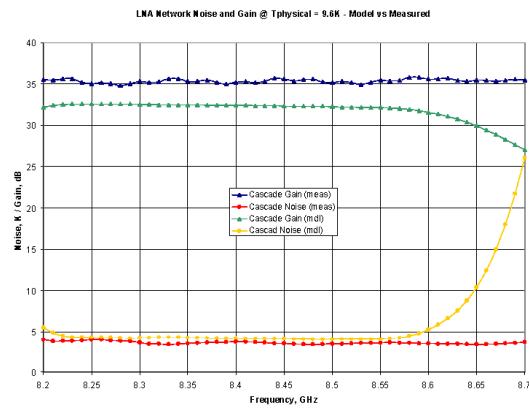
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Photo of Cryogenic, X-Band LNA assembly test bed



Measured and modeled Noise/Gain of four-stage 32GHz InP LNA module



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Subsystem Measurements and Results**

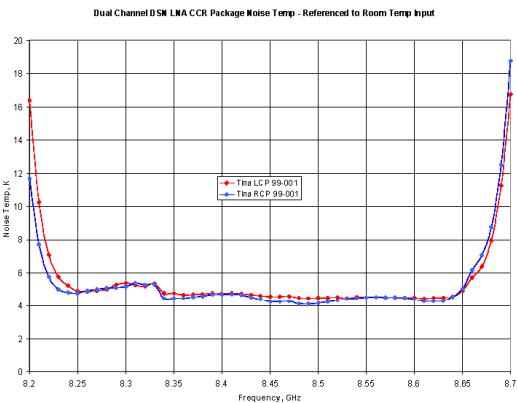
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Photo of DSN Dual Channel InP HEMT/CCR package



Measured Noise Temperature DSN Dual Channel InP HEMT/CCR package



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Deep Space Network, Cryogenic HEMT LNAs
Solution: Beam Wave guide 34m Antenna**

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Photo of DSN X/X/Ka HEMT/CCR package

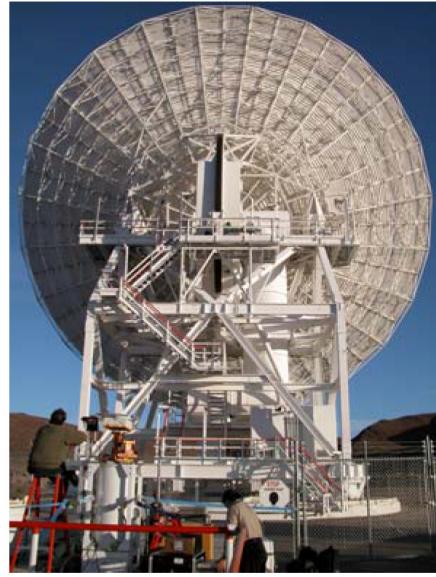


Photo of DSN X/X/Ka HEMT/CCR package prior to installation

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Noise Contributions to Received Microwave Signal**

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Maser with Room Temp Feed vs HEMT with Partially Cooled Feed

NOISE BUDGET WITH XRO FEED (K):		NOISE BUDGET WITH XTR FEED (K):	
COSMIC BACKGROUND	2.5	2.5	
ATMOSPHERE (CLEAR)	2.1	2.1	
ANTENNA/ SUBREFLECTOR	3.8	3.8	
ROOM TEMPERATURE FEED COMPONENTS	1.1 0.8 PCG CPLR ROT JUNCT POLARIZER ROT JUNCT ORTHO JUNC WG SWITCH CAL COUPLER	1.1 0.8 PCG CPLR XMT JUNC XMT FILTER AMB LOAD SW	1.9 OTHER ROOM TEMP FEED PARTS
LNA PACKAGE(S)	5.3 VAC WINDOW CRYO INPUT WG MASER AMPLIFIER 4.9 K CCR POST AMP	3.6 2ND IDENTICAL CHANNEL 6 K CCR	4.8 DUAL CHAN HEMT LNA ISOLATOR BP FILTER ISOLATOR HEMT LNA ISOLATOR POST AMP
FOLLOW-UP CONTRIBUTION	0.3		0.1
TOTAL SYSTEM NOISE TEMP, Top (TYPICAL)	19.5		17.1

SMP 10/04/00

Front-end receiver packages employing these modules typically demonstrate operating system noise temperatures of 17 K at 8.4 GHz (on a 70m antenna at zenith) and 39 K at 32 GHz (on a 34m antenna at zenith).

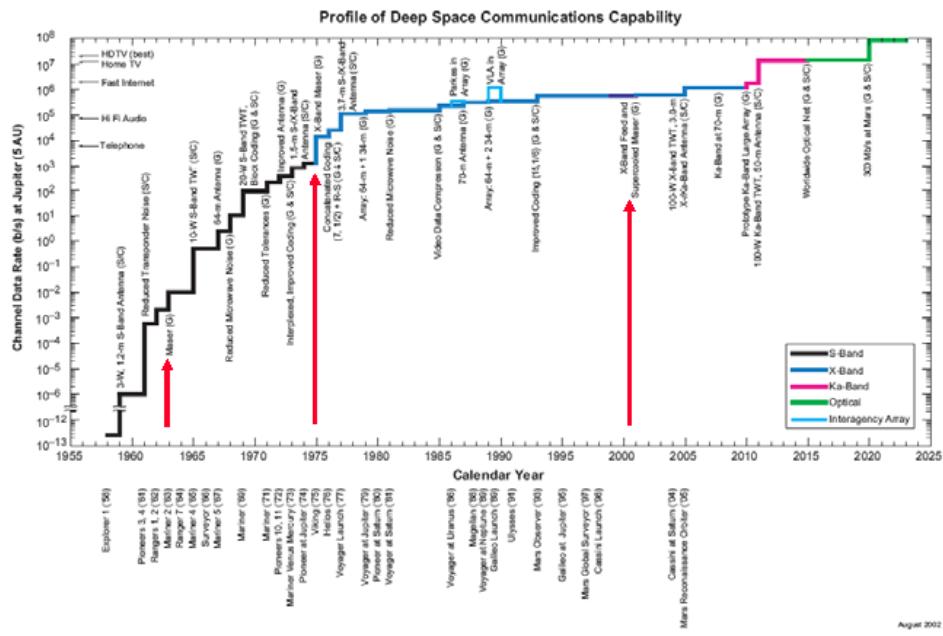
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Conclusion: Data Rate Improvements**

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